GEOLOGY OF THE THREE KINGS ISLANDS, NORTHERN NEW ZEALAND

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Abstract. Three Kings Islands are composed of hydrothermally altered submarine basalt flows and acidic tuff and breccia, represented by spilite and keratophyre (Three Kings Volcanics — new formation), together with closely associated and locally interbedded greywacke (Tokerau Formation). These rocks have been intruded by basaltic dikes and rare sills. The volcanics and associated sedimentary rocks are probably of Cretaceous age, possibly early Cretaceous.

The time of origin of the islands themselves is unknown but they are unlikely to have been joined to mainland New Zealand within the last few million years. The presence of high-level Quaternary terraces preserved on the islands indicates that the area is currently being uplifted.

The Three Kings Islands are situated about 50 km north-west of Cape Reinga, off the northern tip of New Zealand (Fig.1). The group consists of one large island (Great Island), three intermediate-sized islands (West, South West and North East Islands) and a chain of small, high-rising rocks (Princes Islands) (Figs.1,2).

The isolation of the group, the precipitous cliffs and characteristic high seas and strong currents in the area have prevented any previous attempts at comprehensive geological mapping. However, there have been several limited studies, mainly on the geology of Great I. Fraser (1929) noted that Great I was composed of greywacke, but it was Bartrum (1936a, b) who undertook the first geological research, during the *Will Watch* expedition of 1934. He spent one day around North West Bay and Castaway Valley, and collected samples of a pillowed spilite, an "albite porphyry", and a quartz keratophyre, all of which overlay "greywacke basement" near Cave Landing. His detailed petrographic studies of these samples resulted in the first recognition of spilites in New Zealand (Bartrum 1936b). The *Will Watch* expedition could not land on any other islands, and Bartrum had to be content with speculating on their composition from boat-based observations. His incorrect identification of greywacke forming West and South West Is illustrates the difficulty in distinguishing some lithologies from a distance. Thirteen years later, Buddle (1948) landed on South West I and Princes Is, and brought back three rock samples which Bartrum (1948) identified as quartz andesites.

In 1951 Battey (1951) spent 5 days on Great I and produced a preliminary geological map based primarily on cliff-top and inland exposures. His map is basically correct, but his inability to see the well-exposed geology in the encircling cliffs through

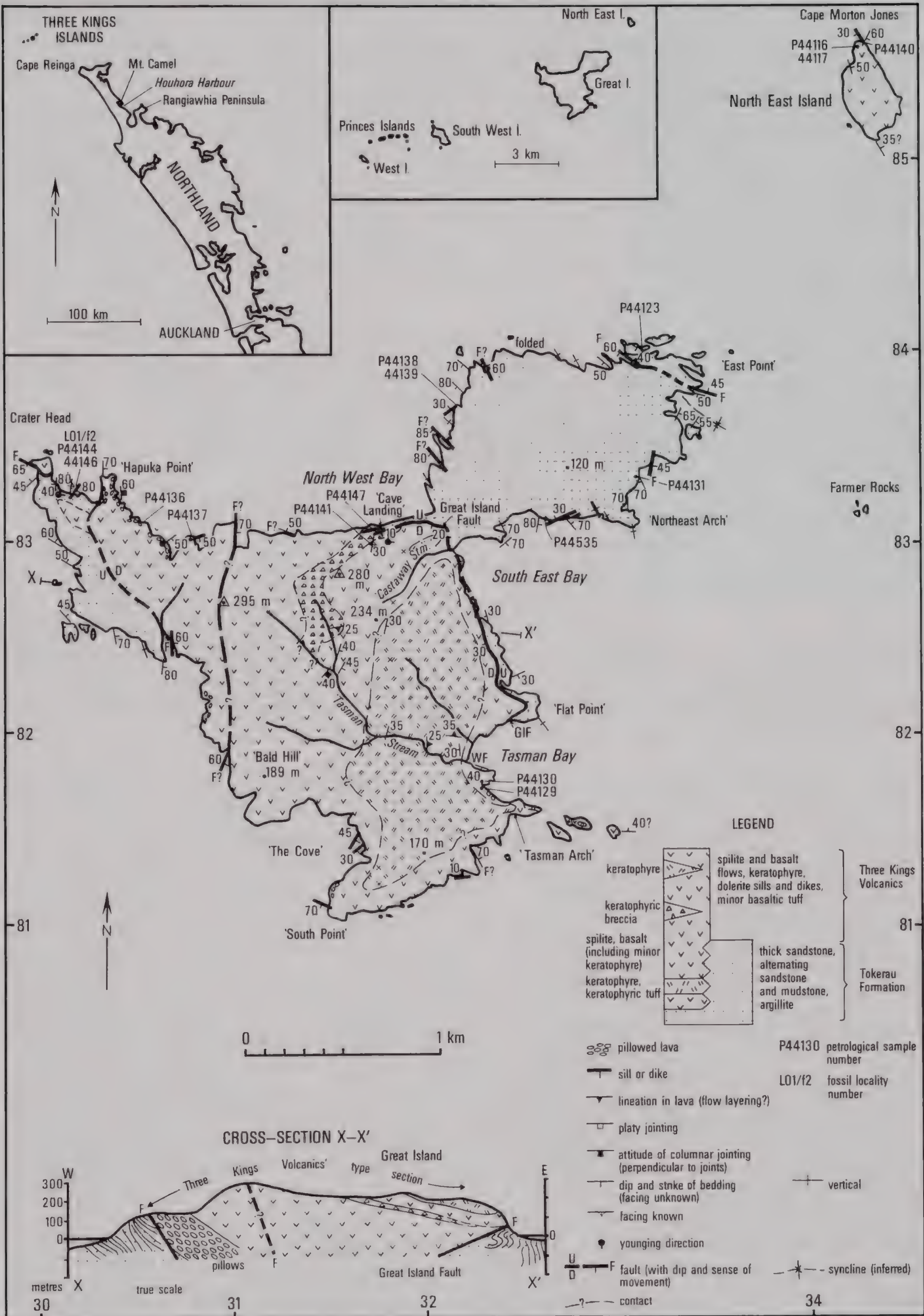

Fig. 1. Inset. Location of Three Kings Is off northern New Zealand. Geological map of Great and North East Is, and cross section through Great I.

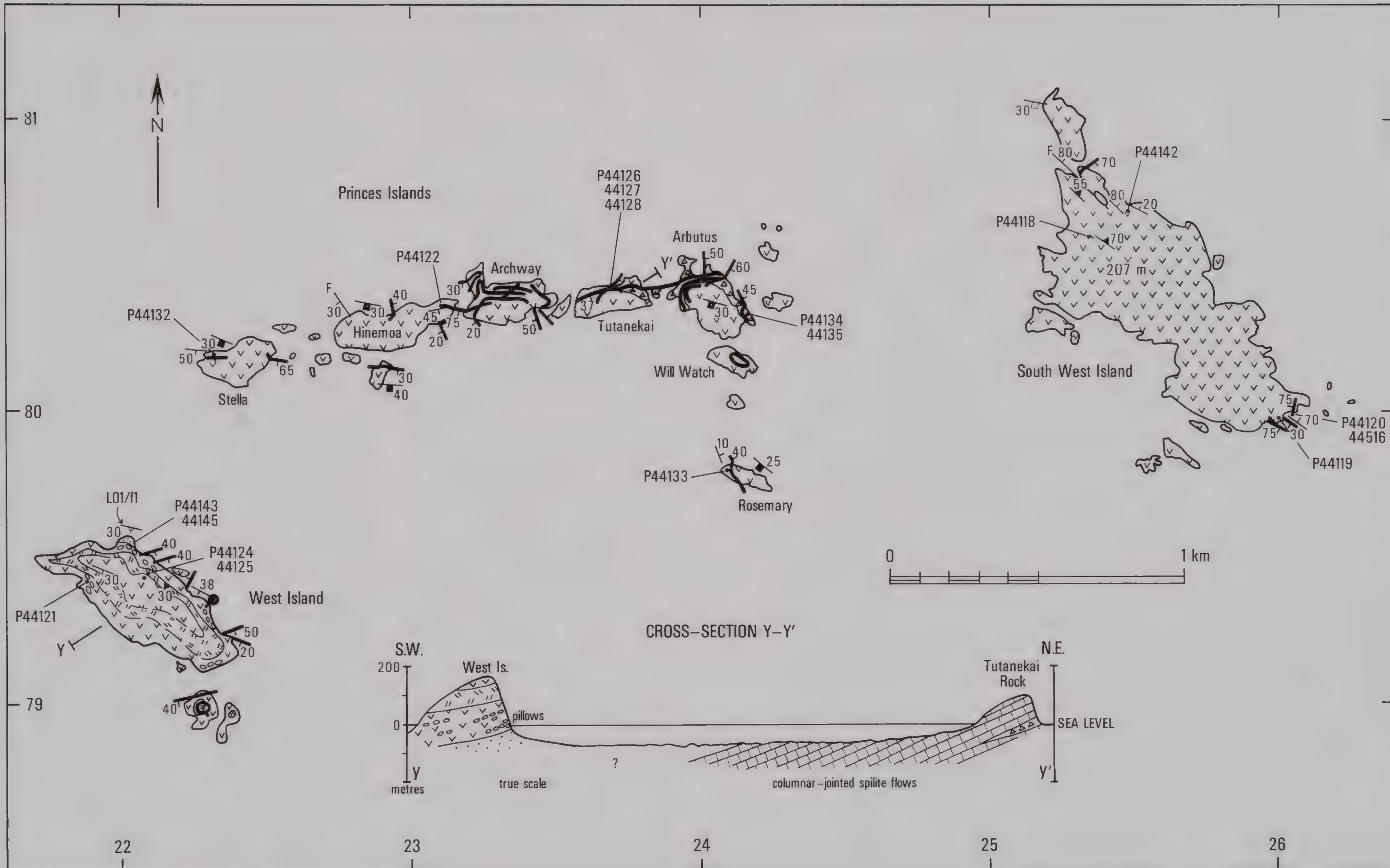

Fig. 2. Geological map of South West, West and the Princes Is, Three Kings Group, and cross section through West and the Princes Is. See Fig. 1 for legend.

the lack of a dinghy, prevented him from realising that the greywacke in the east was faulted against the spilites and keratophyres, rather than overlying them as he postulated. Battey (1954, 1955, 1956) discussed the petrography, petrochemistry and petrogenesis of these Great I spilites and keratophyres, together with similar rocks from Mt Camel and Rangiawhia Peninsula in northern North Auckland.

The other work relevant to the geology of the Three Kings is that of Summerhayes (1969) who produced a geological map of the seafloor in the region, based on dredged rock samples. In the vicinity of the Three Kings, he found the rock suite to be virtually identical to that on the islands themselves.

The authors undertook detailed mapping of the islands during an 8 day visit by the Offshore Islands Research Group in November-December 1983. This was made possible by an exceptionally calm period of weather, and the use of a 5 m rubber dinghy and a 4 m aluminium dinghy. The cliffs of North East, West and Princes Is, and of the north and east coasts of Great I, were examined closely but a shortage of time prevented detailed work around the south and west coasts of Great I or a circumnavigation of South West I. Mapping of inland parts of Great I was considerably hindered by the presently dense scrub cover. Petrography of the Three Kings rocks collected is discussed by Challis (1987 this volume).

STRATIGRAPHY

Tokerau Formation Hay 1975

Sedimentary rocks on the Three Kings include indurated thick-bedded sandstone, alternating sandstone and mudstone, laminated mudstone, and minor conglomerate, here referred to collectively as "greywacke". The northeastern part of Great I is almost entirely composed of greywacke, primarily a sandstone-dominated alternating sequence (Fig.3). Alternating beds also form part of the northwest end of Great I. Elsewhere on the Three Kings, sedimentary rocks are largely restricted to small outcrops of thin-bedded sandstone and mudstone or laminated calcareous mudstone interbedded with volcanics.

Around the north side of South East Bay, the greywacke sequence consists of thick-bedded sandstone with minor mudstone, centimetre-bedded alternating strata (sandstone : mudstone ratio 1:1 to 4:1 or higher), and some mudstone-dominated zones. The rocks are mostly strongly disrupted with pull-apart of sandstones, complex folding, and sheared argillite beds. In places, however, parallel and cross-lamination are seen in sandstone beds. Calcite veins are common locally.

At the northwest end of Great I, between Crater Head and "Hapuka Point", alternating beds (mostly cm-bedded) are particularly well-preserved and a eastward younging direction was determined from sedimentary structures. Included in this sequence is a 1 m thick tuffaceous? bed, concretionary mudstone, and a 6-8 m thick

Fig. 3. Indurated, bedded sandstone of Tokerau Formation in the shore platform near East Point, Great I.

pebble conglomerate (P44146; P numbers refer to samples in the New Zealand Geological Survey petrology collection), composed mainly of concretions and pebbles (mostly < 5mm) of siltstone, sandstone, chert, and keratophyre.

The only other place where the alternating facies is particularly well-preserved is at the north end of West I. Strata here consist of cm-bedded alternating fine to medium grained sandstone and grey mudstone (sandstone : mudstone ratio about 1:1 to 1:2) with a few small calcareous concretions and hard concretionary beds. Sandstones (lithic feldsarenite, P44145) are mostly 1-5 cm thick, but up to 10 cm, graded, and parallel to cross-laminated. Ripple lamination indicates flow of paleocurrents towards the east or NE, assuming a simple rotation of beds. Sole marks include small load casts and scour structures, and some sandstones are noticeably channelised. Mudstone beds have a blocky-cuboidal fracture and contain common trace fossils, although no cross-cutting burrows were seen.

Apart from minor intraformational slumping and numerous small-scale faults, alternating strata at this locality show remarkably little deformation, especially considering the close proximity to overlying pillow lava. This suggests that the sediments were moderately well compacted prior to burial beneath the lava flow.

"Laminated mudstone" interbedded with volcanic rocks, notably in Tasman Valley, at Cape Moreton Jones, and at the southern end of the South West I (P44516), consists mainly of mudstone-dominated, thin to very thin-bedded alternating sandstone and dark grey mudstone. At some localities, sandstone beds are up to 3 cm thick, graded and parallel laminated. Sandstone : mudstone ratio varies from about 1:4 to 1:6 or greater. As in the case of the alternating beds at West I, many of the laminated mudstone units are surprisingly little deformed, and must have been compacted prior to the extrusion of basic lava flows.

Relationship between sedimentary and volcanic rocks

There are several localities where relationships between greywacke and acidic and basic volcanic rocks are well exposed. The most important of these are Cape Moreton Jones (North East I), the cliff face at North West Bay below Three Kings Light, and at the southern end of South West I (Fig.4). At the northern tip of North East I, steeply dipping laminated sandstone and mudstone is conformably overlain by keratophyre,

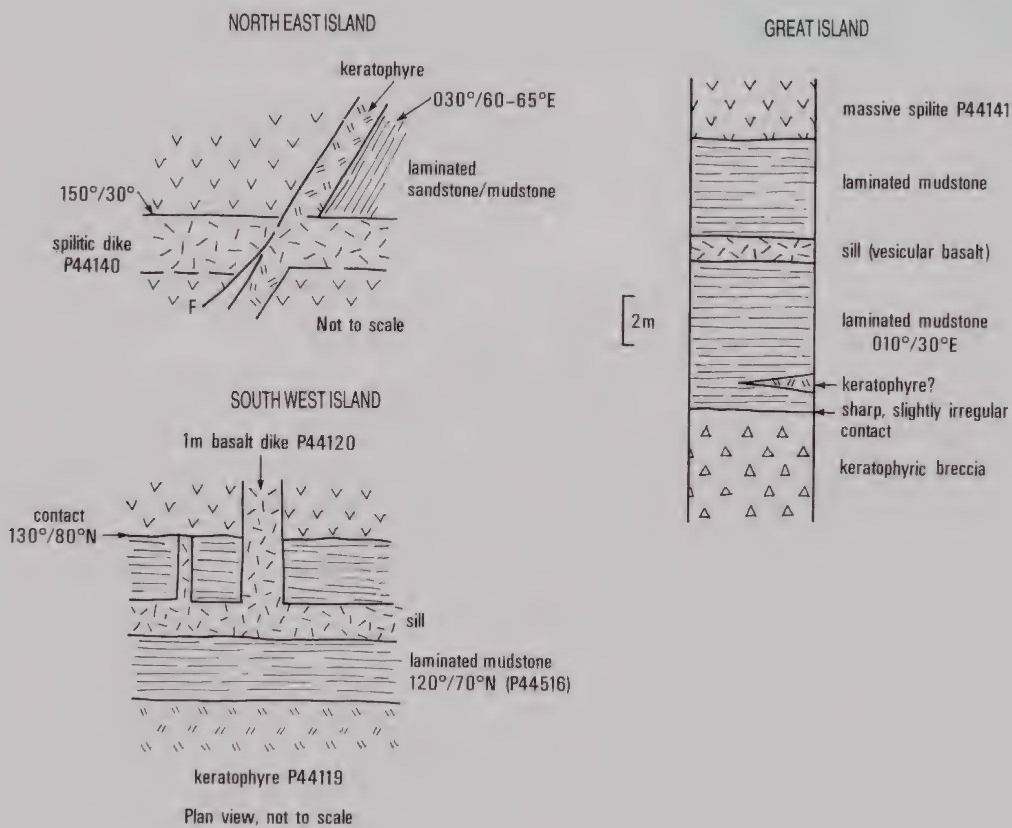

Fig. 4. Detailed relationships between sedimentary and volcanic rocks (based on field sketches). Top left. Northern tip of North East I. Right. Cliff face above North West Bay, Great I. Bottom left. Southern end of South West I.

and both are intersected by a later basic dike (Fig.4). Above North West Bay, on Great I, laminated mudstone overlies keratophyric breccia with a sharp sedimentary contact, and is in turn conformably overlain by a thick spilitic lava flow (Fig.4). Keratophyre may also be interbedded with the mudstone. At the southern end of South West I, laminated calcareous mudstone (P44516) is interbedded with amygdular keratophyre (P44119) and both are intersected by later basalt dikes (Fig.4). At the north end of West I, pillow lava has a sharp contact with underlying alternating beds, and shows local loading into the sediments.

Deposition of the greywacke is obviously closely related in time to emplacement of the keratophyric rocks and extrusion of the spilitic lava flows. Nowhere were dikes of keratophyre found cutting the sediments, although the presence of blocks of argillite up to 1.5 m diameter in keratophyric breccia at North West Bay (below, Fig.4) indicates that greywacke was locally involved in eruption/emplacement of acidic rocks.

Three Kings Volcanics new formation

TYPE SECTION. Cliffs of North West Bay, Great I, from the western base of "Hapuka Point" (L01/303832) to the top of the cliff just west of the saddle (L01/321831) separating North West and South East Bays (Fig.1 section X-X′, Fig.5).

DISTRIBUTION. Three Kings Volcanics are the dominant rocks on the Three Kings Is forming North East, South West and Princes Is, most of West I and the major, central part of Great I (Figs.1,2).

DESCRIPTION. These rocks consist of altered basaltic volcanics (dominantly spilite) and minor altered, interbedded rhyolitic tuff, breccias and possible flows (all keratophyre) intruded by numerous, mostly less altered, basaltic dikes. The majority of the volcanics are sheet-like flows (each 10-200 m thick), with pillow structure well developed in some of the basaltic units and sedimentary layering or flow-banding in some of the rhyolitic units. Thin units of obvious breccia and altered tuff are present locally.

THICKNESS. The sequence at the type section is 750 m thick, but a far greater total thickness is probable.

RELATIONSHIP TO OTHER ROCKS. Three Kings Volcanics are faulted against Tokerau Formation sedimentary rocks on eastern and north western Great I but are seen to conformably overlie Tokerau Formation at Hapuka Point, Great I and the northeastern tip of West I. Thin units (1-10 m thick) of mudstone are sporadically interbedded within the Three Kings Volcanics sequence, especially in Tasman Valley and Tasman Bay on Great I. It is apparent that Three Kings Volcanics and Tokerau Formation are partly contemporaneous seafloor deposits.

Fig. 5. Oblique aerial view of Great I from the north east. Crater Head (foreground) is composed of Tokerau Formation "greywacke" overlain and faulted against spilite pillow lavas at the base of the Three Kings Volcanics' type section. At the east end of North West Bay (far left) the spilites and keratophyres of Three Kings Volcanics are separated from further Tokerau Formation sediments by Great Island Fault.

Photo by Lloyd Homer.

Volcanics of basaltic parentage

The bulk of Three Kings Volcanics are medium to dark grey, massive, platy- or columnar-jointed, vesicular and in places, pillowed, lava flows originally of basaltic composition. Most have been altered to spilite (see Challis this volume). Thin veins of quartz and calcite are locally common and pods (up to 0.3 m across) of green, crystalline epidote occur within basic flows at Cape Morton Jones, north end of South West I and on Tutanekai Rock.

North East I is composed predominantly of featureless fine-grained spilite. At the northern end these lavas contain lenses (up to 1 m thick) of light-coloured keratophyre, a 1.5 m thick packet of Tokerau Formation sediments, and irregular pods of coarse-grained basalt.

The sequence of basaltic volcanics on Great I is best exposed in the type section, along the southwest coast and in Tasman Valley. The lower part, exposed around Hapuka Point, consists of ca. 200 m of pillowed spilite conformably overlying and also faulted against Tokerau Formation (Fig.5). The pillows are mostly elongate, up to 1 m diameter, and their convex upper surfaces confirm an easterly younging direction. The presence of several, more massive tongues of spilite within this pillowed unit indicate that it is composed of a number of lava flow pulses. This is the "spilitic pillow lava" exposure studied in 1935 by Bartrum (1936a, b).

The pillow lavas are conformably overlain by ca. 450 m of virtually featureless, dark grey spilite that is cut by prominent, NW-striking fractures, and possesses occasional epidote pods and quartz veining. The sequence above this includes two thick units of keratophyric breccia and tuff, separated by ca. 70 m of vesicular and partly platy-jointed spilite. Within this spilite are several thin horizons of laminated mudstone.

South West I consists predominantly of massive, grey, basaltic lava with small areas (such as the northern tip) that are structurally complex and contain slivers of intensely altered, calcite-veined spilite interspersed with massive vesicular spilite and fine-grained less altered spilite.

The Princes Is consists of a ca. 350 m thick sequence of east-west striking, columnar-jointed, basic flows that appear to project eastwards into the west side of South West I (Fig.2, 6). Each flow is 15-30 m thick and separated from adjacent flows

Fig.6. Oblique aerial view of most of the Princes Is and South West I (top left) from the north west. These islands are mostly composed of columnar-joined, spilite flows that dip to the south (right) and are intruded by numerous basalt dikes that have been picked out by erosion.
Photo by Lloyd Homer.

by 0.5-1 m thick zones of brecciated spilite. The sequence overlies a wedge of keratophyric breccia (Fig. 2 Y-Y′, 7). In the upper part of the Princes Is sequence on Rosemary Rock, the lava flows are partly pillowed and interbedded with tuff.

On West I, the Three Kings Volcanics are divided into three units (Fig.7). The ca. 70 m thick lower unit of massive and pillowed olivine basalt and minor tuff conformably overlies Tokerau Formation sediments. Packets of pillows within this unit indicate several pulses of lava flow. The convex upper surface and draped lower surface of many of the pillows (Fig.8) show that the sequence is not overturned. This unit is separated from the upper spilite by 40-60 m of keratophyre. The upper, 60 m thick olivine spilite is not usually pillowed but locally platy-jointed and often vesicular.

Volcanics of rhyolitic parentage

A small portion of Three Kings Volcanics consists of orange or speckled grey-white, massive or layered, fine to coarsely crystalline, breccia and ash flows or tuffs, originally of rhyolitic composition. These have been altered to highly quartzose

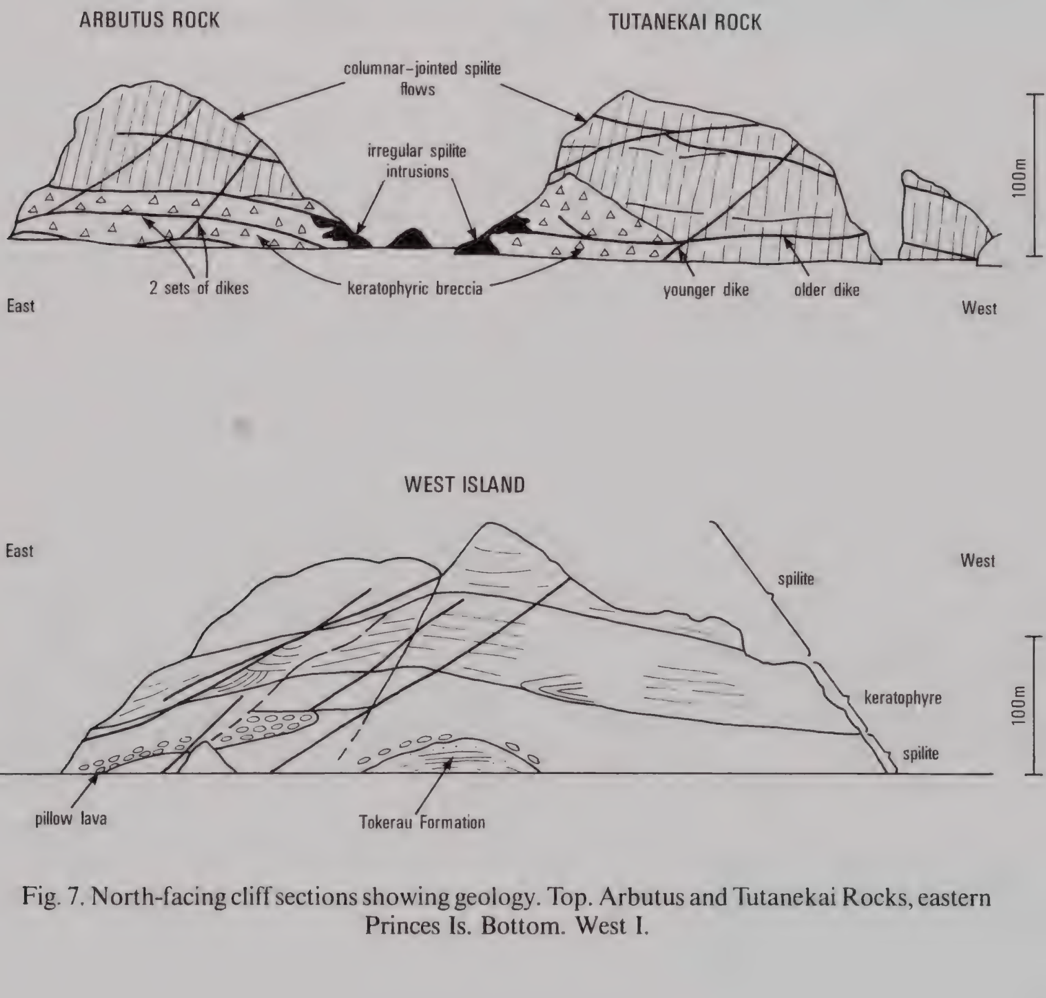

Fig. 7. North-facing cliff sections showing geology. Top. Arbutus and Tutanekai Rocks, eastern Princes Is. Bottom. West I.

Fig. 8. Spilitic pillow lavas (Three Kings Volcanics) exposed in the cliffs on the east side of West I. Hammer 35 cm long.

keratophyres (see Challis this volume). They are distinguished in the field by their light colour, as well as layering or brecciated texture. The three main areas of outcrop of these rocks are on Great, eastern Princes, and West Is.

On Great I, two 30-100 m thick units of banded keratophyre and keratophyric breccia occur within the spilite sequence (Fig.1, X-X′) exposed above North West Bay and in Tasman Valley. Breccia clasts are mostly 3-30 cm diameter and include minor spilite and mudstone fragments.

Near the foot of Tutanekai and Arbutus Rocks (eastern Princes Is), a wedge up to 40 m thick of orange-grey keratophyric breccia occurs conformably beneath columnar-jointed spilite flows and is intruded by irregular tongues of vesicular spilite (Fig.7). In the east, the breccia is fine-grained, green-coloured and monolithologic, whereas to the west, on Tutanekai, the clasts are mostly 3-10 cm diameter and include a mixture of fine and coarsely crystalline siliceous keratophyres together with less common spilite and mudstone.

On West I, a 40-60 m thick unit of banded, orange, pink, and speckled grey keratophyre occurs conformably within the spilite sequence (Fig. 7). The banding is produced by alternating layers of coarse and finely crystalline groundmass, often with the fine layers being more vesicular and weathered than the coarser.

Several thin lenses of keratophyre also occur within structurally complex spilites at Cape Morton Jones, North East I.

Intrusive rocks

All identified intrusive rocks on Three Kings Is are of basaltic parentage. These are most commonly parallel-sided, 0.3-6 m thick dikes with less frequent sills and irregularly-shaped intrusive bodies. The irregular intrusions are spilitised but the dikes and sills have undergone less alteration and mostly consist of coarse-grained basalt (see Challis this volume).

Scattered dikes intrude spilite, keratophyre, and Tokerau formation sediments on North East, South West and Great Is, but the greatest concentration of intrusions is on Princes and West Is. At the east end of Tutanekai Rock, three phases of intrusion are identifiable (Fig.7). The spilite flows and keratophyric breccia sequence is intruded by irregular tongues of vesicular spilite which are cut by a later 2 m thick, oligoclase basalt dike (090/37°S). The youngest intrusion, cutting all these rocks, is a 4 m thick coarse-grained olivine basalt dike (020/35°E).

On Tutanekai and adjacent Arbutus Rock, two sets of dikes intrude the sequence (Figs. 2, 7): an older, low-angle set, subparallel to the spilite flows (080-100/14-40°S) and a younger, steeper set (180-020/35-60°E). Two sets of low and steep angle dikes are also present on Archway and Hinemoa Rocks. On West I, one set of dikes is dominant. These dip at 20-40° to the south-east (Figs. 2, 7).

Very few sills were identified on the Three Kings Is. However, they do occur within Tokerau Formation sediments above North West Bay, between spilite flows on Stella Rock, and at the south end of South West I (Fig.4).

STRUCTURE

TOKERAU FORMATION

On Great I, bedding in the greywacke has a strong N to NW trend. The rocks are tightly folded in places and near 'East Point' strata are probably folded into a SE-plunging syncline. Faulting is widespread, and the shape of the coastline appears to be controlled partly by steep NW-trending faults. Near "Hapuka Point" alternating beds face eastward and are locally overturned.

The degree of deformation is variable; on eastern Great I, bedding is sheared and locally strongly disrupted in contrast to the relatively undeformed sequences at the western end, and on West I.

THREE KINGS VOLCANICS

On Great I, the Three Kings Volcanics sequence is structurally simple, mostly dipping 35-60° to the east or south-east (Fig. 1, X-X′). Approaching the Great Island Fault, the sequence is folded into a gentle syncline.

On West and Princes Is, the Three Kings Volcanics sequence has a consistent 30-50° tilt to the southwest (Fig. 2, Y-Y′). The seafloor geology between West I and the Princes Is is unknown, but if no major fault intervenes, then the spilite-keratophyre sequence on West I would lie ca. 200 m stratigraphically above the volcanics of the Princes Is. The columnar-jointed spilite flows of the Princes Is sequence appear to project into the west side of South West I. The bulk of South West I, however, consists of steeply (55-80°), north-east dipping spilite, and a major structural break probably occurs within the western part of South West I.

GREAT ISLAND FAULT (Fig.3)

In North West Bay, sheared greywacke is faulted against overlying green-grey, fine-grained spilite, and the fault contact dips about 20° SW. The fault is largely obscured to the west, but can be traced along the west side of South East Bay where it appears to dip about 30° W.

This fault is clearly a major feature as it truncates the eastward-dipping volcanic succession forming much of western Great I and probably has a vertical displacement in excess of 500 m (cross-section Fig. 1, X-X′). Whether it represents a low-angle normal fault or thrust fault is uncertain, but it is interpreted here as a normal fault.

QUATERNARY TERRACES

A number of flat or gently sloping terraces are preserved on the Three Kings Islands. The lowest, 70 m a.s.l., forms "Flat Point" between South East and Tasman Bays, on Great I. The largest and most obvious covers most (50 ha) of the north-east portion of Great I (Fig.9). This terrace is at an altitude of 80-110 m and slopes gently to the east. The gently sloping, flat top of nearby North East I is the same height and may be a remnant of the same terrace level. Also at the same elevation (90-110 m) are the coincident crests of the five largest rocks in the Princes Is group (Fig.6).

A slightly higher terrace, at 120-140 m, is present at the southern end of South West I. Flat-topped, coincident ridge crests at higher elevations on Great I are possibly the remnants of a number of even higher terrace levels at ca. 160-180 m, 200-210 m, and 270-280 m (Fig.9).

These terraces were probably intertidal or shallow subtidal marine platforms cut during successive interglacial sealevel stands during the Quarternary (last 1.6 M years) and have been preserved by uplift of the islands. They provide convincing evidence that the whole area has been slowly rising for some considerable time.

Fig. 9. Oblique aerial view from the south west over eastern Great I and North East I (distance). Distinct Quaternary terraces are recognisable at 70 m on "Flat Point" (t_1), at 80-110 m on north-east Great I and North East I (t_2) and flat-topped ridge crests (possibly remnant terraces) at 160-180 m (t_3), 200-210 m (t_4) and 270-280 m (t_5).

Photo by Lloyd Homer.

DISCUSSION

Age and correlation

There is no direct evidence for the age of either the Tokerau Formation or Three Kings Volcanics on the Three Kings Is. Two Tokerau Formation mudstones (L01/f1, f2, Figs.1,2) processed for dinoflagellates, proved non-fossiliferous (G.J. Wilson, pers. comm.).

Throughout Northland, spilite and basalt similar to that on the Three Kings has been assigned to three groups — Whangakea Volcanics, Tangihua Volcanics and Houhora Volcanics. Sedimentary units interbedded or associated with all of these have confirmed Cretaceous fossil ages. Petrographically, the spilites and basalts of Three Kings Volcanics are indistinguishable from those of the Whangakea Volcanics at nearby Cape Reinga and Cape Maria van Dieman (see Challis this volume), which contain intercalated sediments with late Cretaceous foraminifera (Hornibrook & Hay

1978). Whangakea (and Tangihua) Volcanics do not have associated rhyolites or keratophyres, however, and the intercalated sediments are mostly multi-coloured, sheared mudstones, quite different lithologically from Tokerau sediments of the Three Kings.

The spilite — keratophyre — greywacke (Tokerau Formation) association of the Three Kings Is compares most closely with the Houhora Volcanic Group which outcrops on the adjacent mainland around Mt Camel (Hay 1981) and Rangiawhia Peninsula (Hay 1975). The Three Kings basalts and spilites are far less altered than those at Mt Camel and Rangiawhia (see Challis this volume), but all may have been lithologically quite similar originally. At Mt Camel, specimens of *Inoceramus* in Tokerau Formation sediments give a Urutawan or Motuan age (= Albian, late early Cretaceous; Hay 1981). By correlation, an early Cretaceous age is possible for the Three Kings rocks.

The Cretaceous Tangihua and Whangakea Volcanics are variously interpreted as having formed at an ocean ridge, as seamounts, or a combination of these (e.g. Farquhar 1969, Brothers 1974, Ballance & Sporli 1979, Brothers 1983). They mostly occur in discrete fault-bounded blocks that most recent workers have suggested were obducted into Northland from the northeast during the late Oligocene (Brothers 1974, Ballance & Sporli 1979, Brothers & Delaloye 1982). The question of whether Three Kings Volcanics and Houhora Volcanics at Mt Camel and Rangiawhia Peninsula were also emplaced by obduction cannot be answered at the present time. We have no evidence to suggest that they are anything other than in place.

Seafloor rock samples show that greywacke, basic volcanics and rare keratophyre are the dominant rock suite around the Three Kings Is, and extend 30 km to the northeast over Bowling Bank and 30 km to the northwest over van Diemen Bank (Summerhayes 1969). Most of the ridge between Cape Reinga and the Three Kings is composed of basalt and other igneous rocks which were interpreted by Summerhayes (1969) as belonging to Whangakea Volcanics separated from the keratophyres and spilites of the Three Kings by a fault located 10 km southeast of the Three Kings Is.

Geological and island history

About 100-60 million years ago (late early to late Cretaceous), basaltic lava flows and tuffs, and rhyolitic pyroclastic sediments and flows (Three Kings Volcanics) were erupted in the Three Kings region. They accumulated on the seafloor together with mud and sand of the Tokerau Formation, and appear to have built up a considerable volcanic pile. There is no strong evidence for a subaerial or shallow water depositional environment. Rhyolitic pyroclastic flows are erupted from subaerial or shallow water vents but often flow into deep water where they are deposited as laminated tuffs, similar to the Three Kings keratophyres (Yamada 1984). Whether these volcanics were erupted from an ocean ridge or seamount, is purely conjecture.

As the sequence built up the Three Kings were intruded by dikes and rare sills of basalt. Some of these dikes were probably feeders to lava flows being erupted on the seafloor above. Some time after eruption, the flows, dikes, tuffs, and breccias were hydrothermally metamorphosed to spilite and keratophyre. Hydrothermal metamorphism may have been related to a large intrusive body of magma nearby.

With increasing depth of burial beneath a growing pile of flows and sediments, Tokerau Formation rocks were indurated. A major phase of volcanism around northern New Zealand, and probably also the Three Kings area, appears to have ceased about the end of the Cretaceous.

No evidence is available concerning the pre-Quarternary Cenozoic history of the Three Kings. Presumably the Three Kings' rocks remained deeply buried and were deformed and faulted by deep-seated earth movements. At some stage they were gradually uplifted and the overlying and surrounding rocks eroded off.

When the Three Kings area first became land is unknown. The bathymetry of the surrounding sea and the evidence of considerable Pleistocene uplift indicates that the Three Kings landmass has probably not been connected by land to Northland at any time during the Quaternary (last 1.6 M years), nor probably for a long time prior to that. The sea gap was possibly narrowed to ca. 25 km during several glacial periods of lowered sea level (most recently only 18,000 years ago). At this time, when sea level was 100-120 m below present, all the islands of the present Three Kings group would have been joined together.

The Three Kings owe their shape to erosional processes that have occurred in the last million or so years as sea levels have fluctuated up and down during alternating glacial and interglacial periods. During this time the whole area has been slowly rising, so that extensive platforms carved out at intertidal or shallow subtidal depths during extended periods of high, interglacial sea level are now uplifted and recognisable on the islands as contiguous ridge crests and terraces. Terrestrial erosion has modified many of these uplifted marine platforms and carved out the stream valleys on Great Island. Most of the present seacliffs drop straight down into deep water and have been carved out by sea erosion during both high and lowered sealevels throughout the Quaternary.

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